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18 June 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2002-157**
S.F. Engelman (ERC) et al., "Hemispherical Measurements of the SPT-140 Plume"

AIAA JPC

(Statement A)

(Indianapolis, IN, 8-10 July 2002) (Deadline = 08 Jul 02)

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PHILIP A. KESSEL Date
Technical Advisor
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Hemispherical Measurements of the SPT- 140 Plume

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The results of a 3-dimensional hemispherical Faraday probe rake assembly are investigated. Such a system is attractive because it allows measurement of current density at multiple locations simultaneously, and can be used to detect asymmetry in the Hall Effect thruster (HET) beam. For ease of correlation, experiments were conducted using Faraday probes and biasing techniques similar to other organizations within the EP community. Results can be used to validate simulations and to gain an understanding of the proper positioning of HETs on spacecraft. Additionally, the effects of varying the Faraday electrode material are presented.

Introduction

As the popularity of Hall Effect thrusters (HETs) increases so does the demand to understand the physical properties such as plume evolution and unique thruster characteristics. This data can then be fed into on-going modeling and simulation programs used to determine the proper placement of HETs on spacecraft.¹

The Air Force Research Laboratory (AFRL) at Edwards AFB built a long-duration test facility capable of testing HETs up to 5 kW for periods greater than 7000 hours. Fig. 1 shows an SPT-140 firing in the test facility.

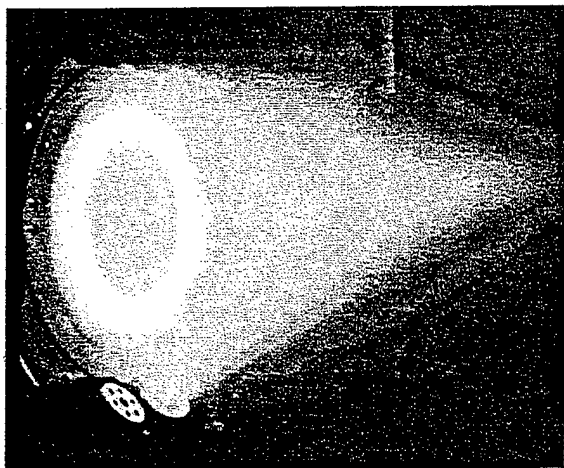


Fig. 1. Fakel SPT-140 Demonstration Model 3 (DM3) firing in AFRL's long-duration test facility.

The test facility was designed with instrumentation to accurately measure ion flux emitted by HETs in two dimensions. Thus, changes in plume divergence and mean flux ion vector over the life of an engine may be quantified. This paper presents initial results from this instrumentation, including SPT-140 ion flux mapped over a hemisphere downstream of the engine, and some comparisons between results from different types of ion flux measurement systems.

Experimental Configuration

AFRL's long-duration HET test facility² (Chamber #3) was selected to conduct these experiments: as it is well suited for testing of HETs. The chamber is constructed of stainless steel with an internal diameter of 3.3 m (10.8 ft) and length of 8.0 m (26.2 ft). All surfaces that are optically visible to the thruster have been covered with ½ inch thick high purity, sulfur-free carbon plate. The thruster exit plane is located in the center of the chamber diameter pointing down the long axis of the chamber, approximately 7 meters from the far end (Fig. 2). Rough vacuum is achieved in the chamber through the use of a dedicated dry Stokes mechanical pump with a pumping speed of 450 l/s. Pumping is achieved through the use of eight helium-cooled cryo-panels: four 0.6 m (1.9 ft) by 2.0 m (6.5 ft), and four are 0.6 m (1.9 ft) by 2.5 m (8.2 ft). Each cryo-panel is shrouded by Polycold® baffles, equipped with a silicon-diode temperature sensor and temperatures are read using Lakeshore 218 temperature monitors. Light gasses are pumped using a 3,000 l/s Balzers turbomolecular pump.

Chamber pressure is continually monitored using a Granville-Phillips 370 Stabil-Ion Controller and matching hot ionization gauge calibrated for xenon. Pressure is measured 40 cm behind the thruster with a 10 cm stainless 'snout' and guard screen to exclude ions. Typical base pressure is

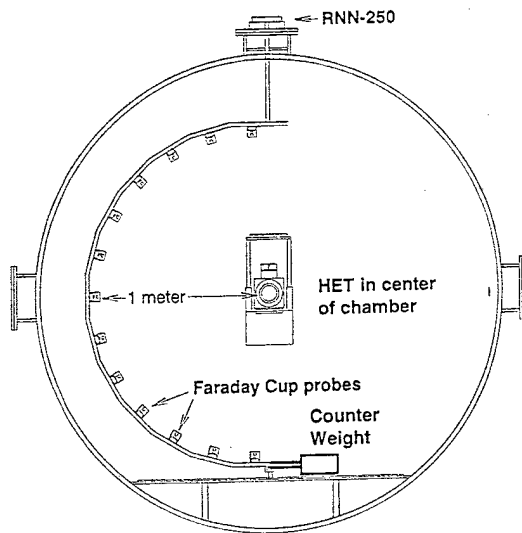


Fig. 2. Cross sectional view of Chamber #3

approximately 5×10^{-8} torr. Pressures during thruster operation are 1.5×10^{-5} torr.

For HET plume measurements, a Faraday rake assembly was constructed. The rake consists of an array of 13 identical Faraday probes approximately 1 meter from the thruster face. As shown in Fig. 2, the 13 Faraday probes were attached to an aluminum tube bent in a hemispherical arc, with the probe face located 91 cm (36 in.) away from the thruster exit plane. The hemispherical design of the probe holder assembly ensures each probe face is normal to the thruster exit. Each probe position and pointing direction has been verified using laser alignment to be within ± 1 cm and ± 3 deg. Angle measurements are defined as: ϕ measurements in the vertical and θ measurements in the horizontal. Probes are separated by 15° intervals along the aluminum tube assembly (ϕ). Also attached to the aluminum tube is a counterweight to reduce lateral loads on the rake bearings. Initially, data was taken at 2° increments in θ for the entire 180° exit plume, however it was later changed to 0.5° to increase the resolution of the probes. Data was recorded using an Agilent 34901A 20-channel multiplexer voltage-reading card placed in an Agilent 34970A Data Acquisition/Switch Unit. Movement of the Faraday probe assembly is provided by an external RNN-250 Thermionics Northwest, Inc. rotary platform with an RFH-450-1.33-8 custom feed-through 'hat' assembly. The external location of the motor and position encoder allow ease of maintenance during thruster operation and an increased lifetime since the motor is not exposed to vacuum or plasma. Computer control is achieved using a Thermionics Northwest, Inc. Stepper Motor Controller 3.5-1 with RS-232 connection.

Faraday cups were designed similarly to probes presented in previous work by NASA and AFRL.³ Probes consist of 4 major components; a collector, a guard ring, holder, and stainless steel threaded rods for electrical connections. Collector and guard rings are made of molybdenum for sputter suppression while in the plasma source, and for its

expected low secondary electron emission yield. Carborundum's Combat® AX05 was selected for probe holders as it has a superior durability in high temperature and vacuum environments.

Biasing and current measuring techniques were done to replicate the SPT-140 tests at University of Michigan and NASA Glenn. The current drawn by the probes is found by measuring the voltage drop across a resistor. Probes are biased to -30 volts with respect to ground in order to repel electrons. -30 volts was found to be well past the saturation point of the probes at 91 cm. (Fig. 3)

Current drawn by the Faraday probes is determined by measuring the voltage drop across a ballast resistor. Sizing this ballast resistor is done by calculating the area ratio between the guard ring and the collector and then matching an inverse relationship with the resistor size as closely as possible. The area ratio between the collector and guard ring is 3.85 to 1. The resistors selected were German made 162Ω $0.6W$ 1% metal film for the collectors and 40.2Ω $0.6W$ 1% metal film for the guard rings. Matching the resistance in this fashion causes the current sheaths surrounding the probe to be virtually parallel and at equal potential to the surface of the guard ring. Ideally the gap between the guard ring and collector would be on the order of a Debye length, however machining limitations prevented this from being achieved.

Data control and acquisition is maintained by a Dell Dimension XPS T500 IBM-compatible desktop computer operating Windows 98® and LabView 5.1®. Connection to the Thermionics Northwest, Inc. Stepper Motor Controller is through an RS-232 cable, while the Lakeshore 218 temperature monitors, Granville-Phillips 370 Stabil-Ion Controller, and Agilent 34970A use GP-IB. Control and operation is fully automated within LabView software, which also provides ability to perform thrust-stand calibrations and

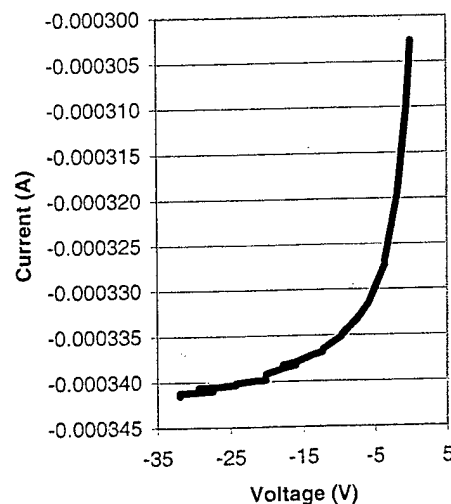


Fig. 3. Ion saturation point is found to be -5 volts.

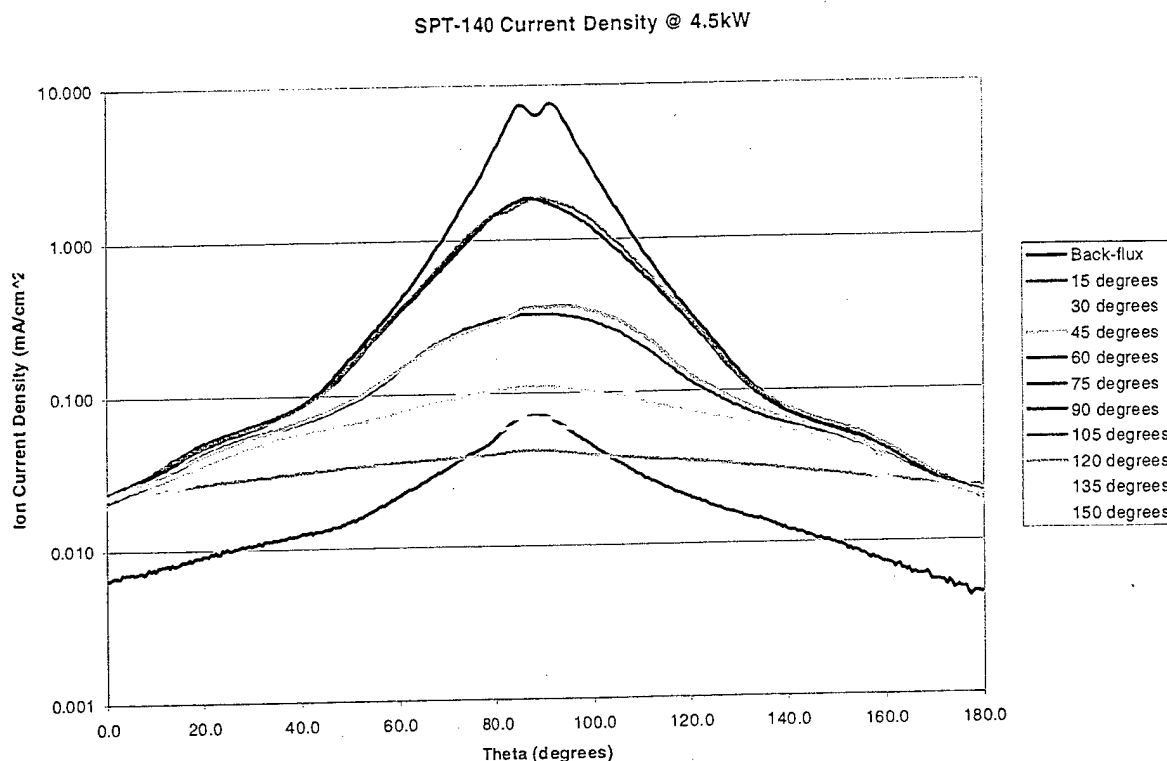


Fig. 4. Measurements of SPT-140 DM3 plume (15A discharge current).

provide warnings when recorded data exceeds user-selected limits (Figure 3).

Parameters are recorded and monitored while the thruster is operating, including propellant usage (mass flow rate), thrust, input power, temperatures, and chamber pressure. In addition to these measurements are the voltage measurements from each Faraday probe shunt. The resulting data provides a two-dimensional map of the diverging plume.

Hemispherical Data

Much data has been collected on HETs in labs around the world, but most experiments rely on only one sweeping probe. The Faraday rake assembly presented here collects data from 11 different probes at the same time. The resulting data shown in Fig. 5 was taken on a single sweep. Variance between individual sweeps is found to be less than 3%.

Integration of the discharge current data in Fig. 4 gives a total current of 17.3 A. This is approximately 15% higher than expected.

Back-Flux

One possible source of the additional ion current collected is slow ambient ion density produced by charge-exchange collisions between primary beam ions and neutral xenon gas in the chamber. To quantify this effect, a Faraday probe was pointed 180° opposite to the centerline ϕ probe (#7). This probe is expected to measure only the randomly directed charge exchange ion current, while excluding the directed ion current from the engine. However, as Fig. 5 shows, the current density from this probe measured less than 5% of the forward-facing probe. Therefore, the 15% additional current is not believed to be caused by randomly directed slow ions. Two possibilities are that the charge exchange ions have some significant directed component, or the additional current collected is due to some anomalous effect at the probe surface.

Novel Probes

One possible surface effect may be related to secondary electron emission of the probe surface. Secondary electron theory postulates that some of the primary ions in the thruster plume have enough energy to knock off electrons from the

probe, effectively doubling the net current measured. Two approaches were taken to investigate this: a) What happens to the current density measurements if the probe is constructed differently than prior probes, and b) What role does the material play in the measurements of ion current density?

Variation in Probe Geometry

Two probes were built to experimentally compare the effect of secondary electron emission. The first probe was designed using the same material as the standard molybdenum probes. However instead of having a disk-shaped electrode, a 20 mm deep cup was substituted. The idea was that a large fraction of the electrons that were knocked off the molybdenum would then be recaptured. Next another probe was constructed out of ELSI carbon velvet. (ELSI developed this velvet as an ion suppression material, and distributes data showing that it has an order-of-magnitude lower sputtering than that of pure carbon.) A 19mm disk of the velvet was used in place of the molybdenum electrode. These probes were then placed one on either side of the centerline probe #7. This way data collected from the new probes could be directly compared with data taken from the conventional molybdenum probe. The probes were separated by approximately 5° . What was found is that the cup shaped probe measured more current than did the molybdenum and the velvet probe collected slightly less. The slight variances, although not enough to explain the 15% additional total current collected, may be attributable to minor alignment error between the rake and the thruster's centerline.

Variation in Electrode Material

To further explore the possibility that surface effects modify the collected current, the velvet and cup probes were replaced with an aluminum and carbon collectors that were identical in construction to the molybdenum collectors. As Fig. 6 shows, the measured currents are nearly identical. They fall within the uncertainty of the measurements themselves. The shift in each curve is due to the difference in cup positions. Therefore, it is safe to conclude that, at 91 cm, probe material is not critical to accurate measurements of the plume density of an HET.

Future Work

Upcoming research will include similar analysis of several HETs commercially available as well as a newly designed laboratory HET. A comparison will be available in the near future.

Currently resolution in the ϕ axis is limited to 15 degrees, due to the fixed arrangement of Faraday cups. An array of more probes inside 30° of the thruster's centerline axis should allow for higher resolution plume analysis.

Finally, work will expand on the effects of probe material by varying the distance from the thruster.

Effect of Backflux on SPT-140 at 3 kW

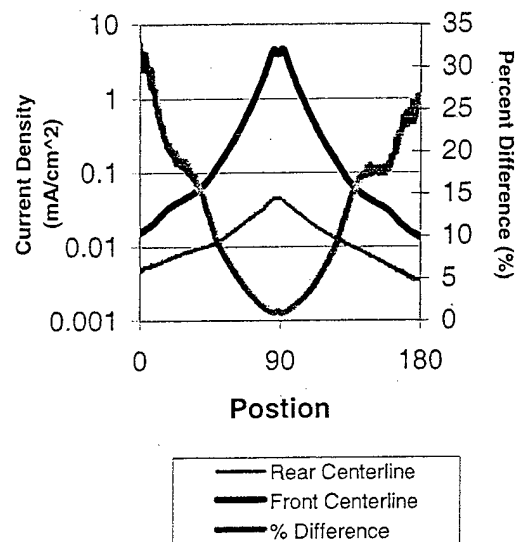


Fig. 5. Plotted is the % of back-flux relative to the measured ion current density at that point. Clearly the effect is larger at the sides of the chamber where the distance to the wall is smallest.

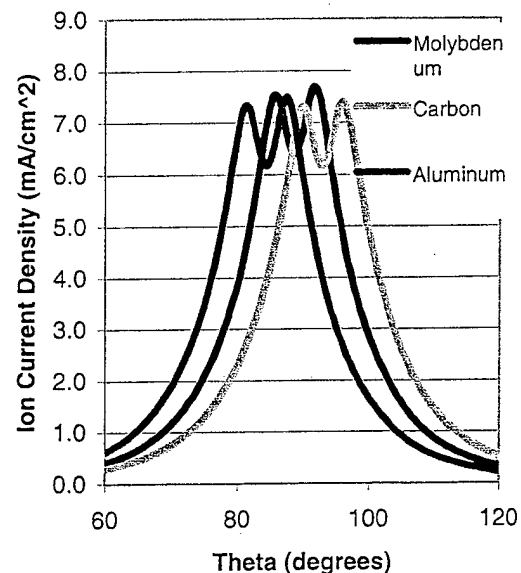


Fig. 6. Comparison of measured current density between the aluminum, carbon and molybdenum.

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³Fife, J. M. et al., "Spacecraft Interaction Test Results of the High Performance Hall System SPT-140," AIAA-2000-3521, 36th AIAA Joint Propulsion Conference, Huntsville, Alabama, 17-19 July 2000.